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14. ABSTRACT
High layer quality GaN NDR layers have been grown in house by newly set up MOCVD facility. Record quality A1N layers were grown for high thermal conductivity substrateless diodes with improved thermal management. GaN Gunn diodes were designed and fabricated on Si substrates with high thermal conductivity. Combined with the use of small size devices they allowed to bias GaN NDR diodes under electric fields suitable for oscillation. Liquid Nitrogen Characterization of GaN NDR diodes manifested clear increase of current handling as necessary for establishment of NDR conditions. Planar GaN NDR diodes have been investigated as an alternative to vertical designs. InGaN/GaN superlattice designs have been theoretically and experimentally investigated for THz signal generation. Pulse generation setups have been developed to respond to high power, nsec time needs of GaN NDR diodes. On wafer probe techniques with built-in resonators have been investigated for high frequency testing of NDR diodes. Experimental micromachining technology was developed for silicon. Waveguide, probes, transitions and flanges developed and tested in W band. Excellent experimental results were obtained in W band. Nearly finished with corresponding GaAs process technology. Technology demostration was made with complete W band multipier.

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Solid State THz Sources

FINAL REPORT

September 23, 2003

The University of Michigan

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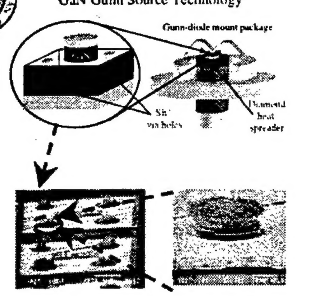
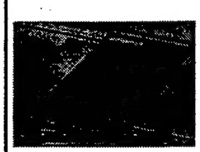
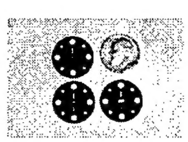
GaN Gunn Source Technology





W-band wavegide Transition



Waveguide flanges

Goals, Objectives and Main Technical Approach

Develop solid-state THz sources using GaN NDR (Negative Differential Resistance) diode oscillators and micromachining..
The NDR devices can further be integrated using low-cost power combining networks and cavities operating at Terahertz frequencies.
Silicon micromachining has been selected as the enabling technology of building blocks for circuits and systems at THz frequencies.Micromachining technology is used for the fabrication of scaleable THz structures

Major Impact of Technology and Accomplishments

The use of wide bandgap GaN-based semiconductors is expected to result in increased operating frequency of Gunn-effect enabling for the first time, THz signal generation using solid-state Gunn diode oscillators.
Micromachined structures are low cost alternatives that can batch produce a variety of components needed at submillimeter frequencies. The major impact of this research will be to greatly reduce the cost and development time of THz circuits
GaN Gunn diodes were designed and fabricated on Si substrates with high thermal conductivity. Combined with the use of small size devices they allowed to bias GaN NDR diodes under electric fields suitable for oscillation.
Deep RIE technology has been optimized for waveguide and probe fabrication. Initial results show excellent insertion and return loss over W band.

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Program Objective and Strategy

Develop solid-state THz sources using GaN NDR (Negative Differential Resistance) diode oscillators and micromachining..

The NDR devices can further be integrated using low-cost power combining networks and cavities operating at Terahertz frequencies. GaN bulk NDR devices are explored as possible THz sources and other alternatives such as SL and Schottky tunnel designs are evaluated.

Silicon micromachining has been selected as the enabling technology of building blocks for circuits and systems at THz frequencies. Silicon and GaAs technology is used to micromachine THz structures. W band multipliers are used as a proof of concept and extension of the technology to submillimeter wave and THz frequencies is envisaged.

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Technical Challenges

- Transport properties and Negative Differential Resistance Properties of GaN and Nitride-Based Compounds
- Low defect concentration of nitride surfaces exposed to deep etching.
- Efficient thermal dissipation in GaN-based NDR devices
- Substrate removal, packaging and testing of high power GaN NDR devices.
- Combination of micromachined structures with sources
- Process development for DRIE depths deep enough to allow waveguide fabrication
- First demonstration of deep etch technology in GaAs for submillimeter applications
- Design and development of circuit elements limited by technology geometries

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Key Milestones

- High layer quality GaN NDR layers have been grown in house by a newly set up MOCVD facility
- Record quality AlN layers were grown for high thermal conductivity substrateless diodes with improved thermal management.
- GaN Gunn diodes were designed and fabricated on Si substrates with high thermal conductivity. Combined with the use of small size devices they allowed to bias GaN NDR diodes under electric fields suitable for oscillation.
- Liquid Nitrogen Characterization of GaN NDR diodes manifested clear increase of current handling as necessary for establishment of NDR conditions.
- Planar GaN NDR diodes have been investigated as an alternative to vertical designs.
- InGaN/GaN superlattice designs have been theoretically and experimentally investigated for THz signal generation.
- Pulse generation setups have been developed to respond to high power, nsec time needs of GaN NDR diodes. On wafer probe techniques with built-in resonators have been investigated for high frequency testing of NDR diodes.
- First DRIE fabricated waveguides in WR10 and WR3
- Fully micromachined transitions covering full waveguide band in WR10
- Fabrication of state of the art planar monolithic W band multipliers
- GaAs deep etch technology

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Technology Transition/Insertion/Commercialization Plan

- We have established various collaborations with government and industry laboratories for advancing, testing and using the developed technology. This includes manufacturers of Gunn diodes and government/academic laboratories.
- Proposals to NASA Glen and NASA JPL for further work at THz frequencies
- ARO MURI research program to develop low cost sources for chemical and biological sensing applications

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Outline

- Introduction
- THz GaN NDR diode oscillators
- THz Micromachined Structures
- Conclusions

THz GaN NDR diode oscillators

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Outline

- Introduction
- Operation of GaN NDR diode oscillators
- Development and optimization of fabrication technology
- Fabrication of GaN NDR diodes
- Si wafer thinning technology
- Electrical characterization of NDR diodes
- Packaging and RF testing of GaN NDR diodes
- Conclusions

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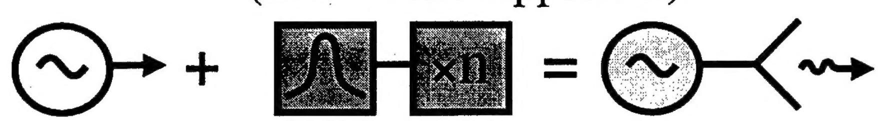
Solid-State Terahertz Sources (The UofM Approach)



GaN NDR Diodes for THz signal Generation

Micromachined Resonator; Filter/Multiplier

Solid-State Terahertz Source

- Unique approach combining new semiconductor and micromachined concepts
- Semiconductor device potential for high-power fundamental or harmonic sources
- Possibility to apply micromachined concept to other sources developed under this program

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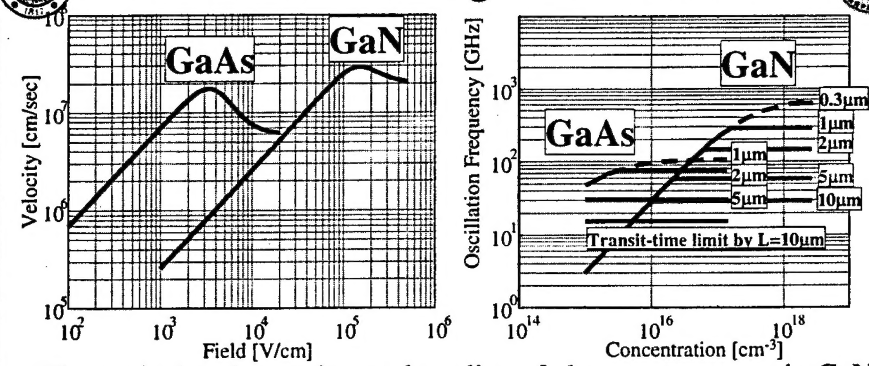
Use of GaN for Signal Generation



- Theoretical and experimental studies of electron transport in GaN predict critical field >*150KV/cm* and peak velocity >2×*10⁷cm/s*
- Maximum frequency of oscillations in NDR devices is limited by the energy-relaxation and intervalley relaxation time.
  - Frequency of GaAs Gunn diodes is limited by electron scattering at ~*100GHz* , while in GaN this limit is at ~*800GHz*

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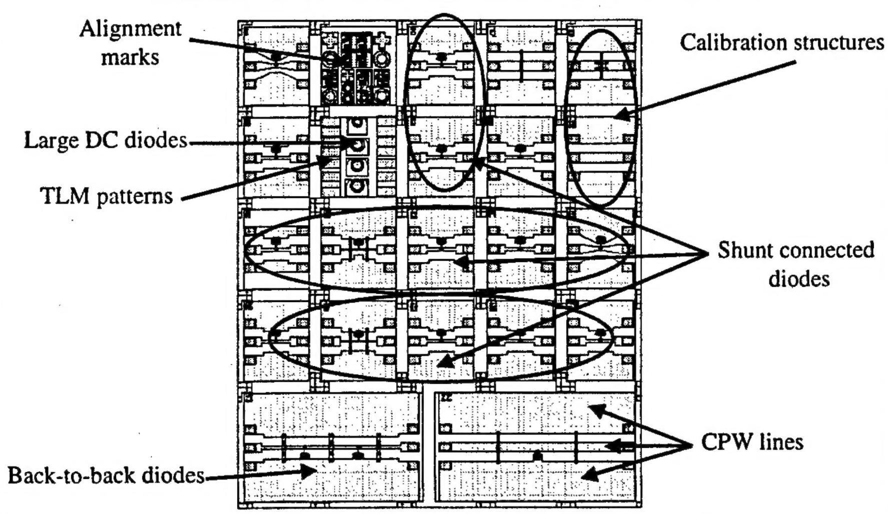
GaN NDR Diode Fabrication Mask Set for Small Size Diodes



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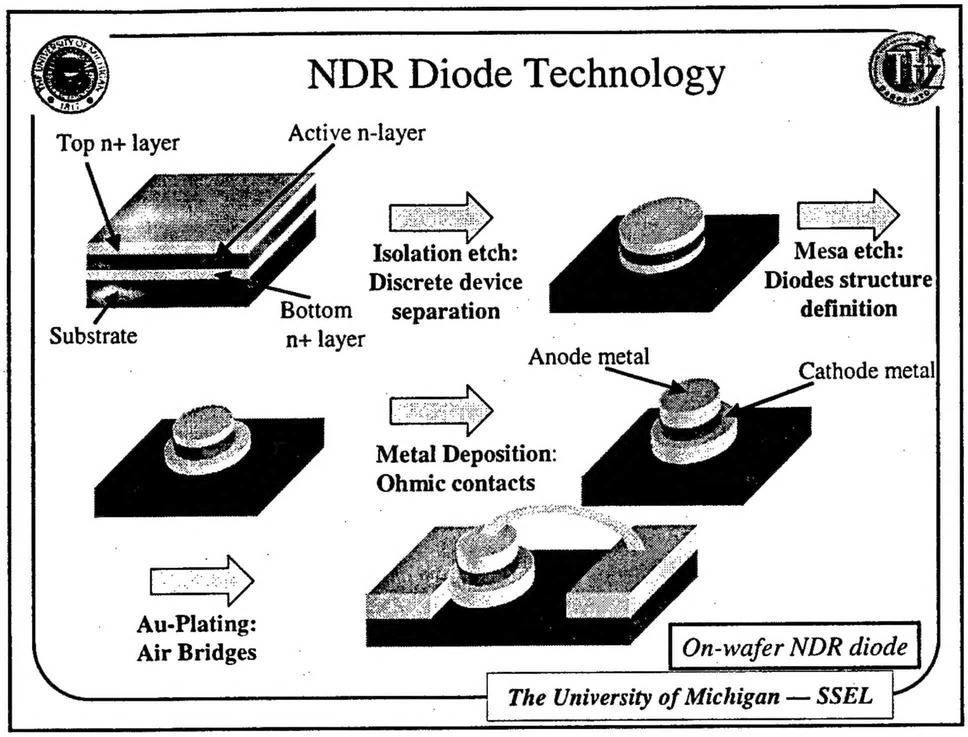
NDR Diode Technology
Top n+ layer
Active n-layer
Substrate
Bottom n+ layer
Isolation etch: Discrete device separation
Mesa etch: Diodes structure definition
Anode metal
Cathode metal
Metal Deposition: Ohmic contacts
Au-Plating: Air Bridges
On-wafer NDR diode
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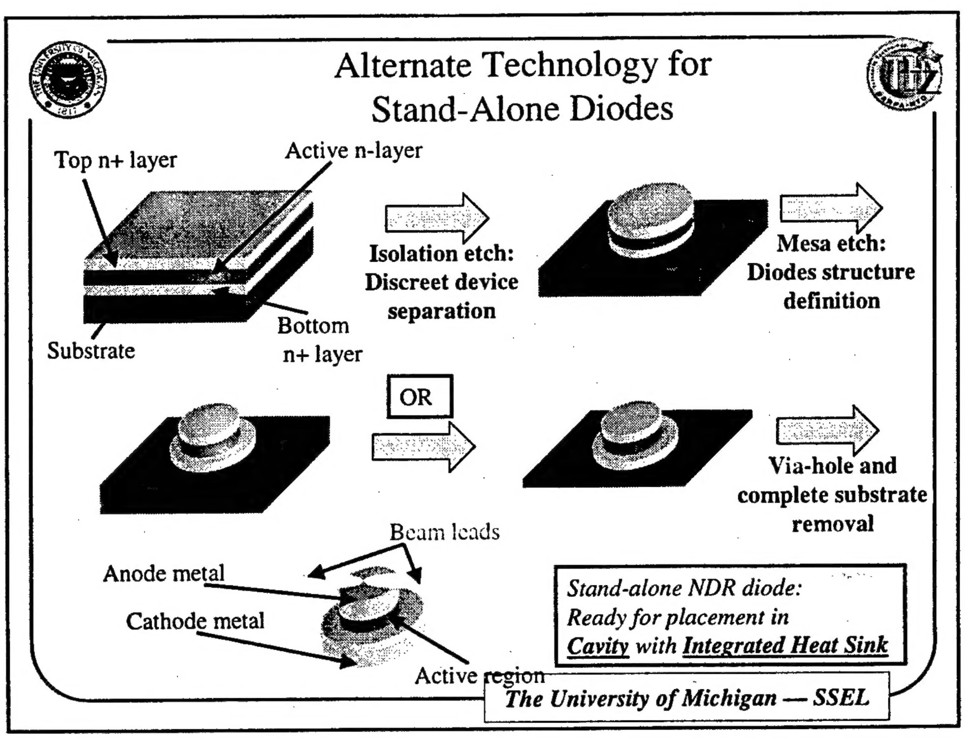
Alternate Technology for Stand-Alone Diodes
Top n+ layer
Active n-layer
Substrate
Bottom n+ layer
Isolation etch: Discreet device separation
Mesa etch: Diodes structure definition
OR
Via-hole and complete substrate removal
Beam leads
Anode metal
Cathode metal
Active region
Stand-alone NDR diode: Ready for placement in Cavity with Integrated Heat Sink
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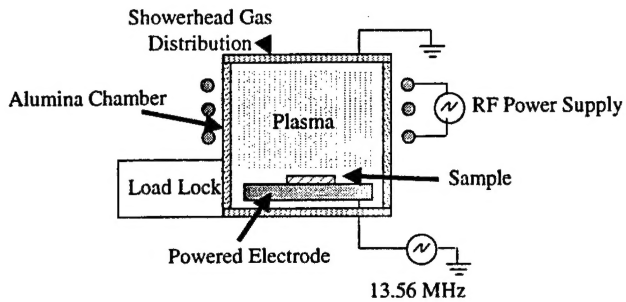
ICP Etching



- Unlike RIE that uses parallel plate reactor, ICP utilizes inductively coupled plasma
- ICP has several **advantages** over RIE:
  - ° Operation over wider range of pressures (1 – 500 mTorr)
  - ° Plasma density increases linear with power up to high power levels
  - ° ICP can produce more anisotropic etches compared to RIE
  - ° Plasma is usually more dense leading to chemical etching enhancement
    ⇒ **Less surface damage**
  - ° ICP allows better selectivity between the etched and the masking materials

Etching of GaN:
Sample UMTS125 with 100 nm n+ GaN (1e19 cm-3) cap layer, 1 micron n- GaN active layer (1e17 cm-3), 500 nm n+ GaN bottom contact layer (8e18 cm-3), 1.96 microns u-GaN (4e16 cm-3) and a 20 nm LT-NL (nucleation layer ?).

Sample description:
A-type: mesa etching with 5 microns thick AZ4562 resist mask (targeted etch depth: about 1300 nm)
B-type: mesa etching with a combination of Ti/Al/Ti/Au-metallization (22nm/78nm/22nm/83nm) and 1.5 microns thick HiPR6517 resist as mask.

Test samples: AZ4562 on glass, the B-structures with and without photoresist on Glass (possibility to determine the etching rate of photoresists and metallisations)

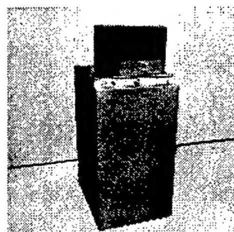
Etching machine: Oxford Instruments Plasmalab 80plus RIE system
Gas: SiCl4, 5 sccm
Base pressure: 8E-6 mbar
rf power: 200 W
measured self-bias: between

Etching procedure: 15 min etching, 10-25 min break for the pressure to recover

Test results: 3x15 min etching + 2x10 min break
etch depth of AZ4562: 1500 nm
etch depth of glass: 100 nm
etch depth of GaN: 760 nm (17 nm/min)

2d Batch: 76 min etch + breaks, etch depth of GaN: 800nm (11nm/min)
expected etch depth: about 1300nm. Reason: silicide formation slowing down the process.

3d batch to continue the etching, after cleaning of the chamber !!, 15+10+10 min etching and 25+15 min break, etching depth 1600-1700 nm. After cleaning the chamber higher etching rate was observed.



Plasmalab 80Plus for RIE

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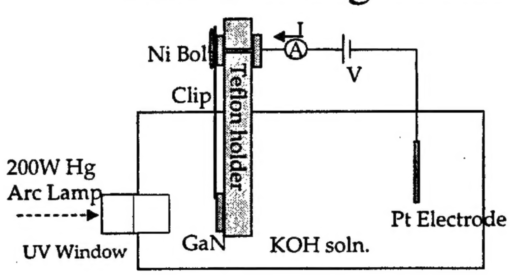
PEC Etching of GaN



- Etching of GaN occurs due to Photo-electro-chemical reaction at sample surface
  - Arc lamp induces photo-generated e-h pairs in GaN
    - Excitation provided by newly acquired 200W Oriel Hg arc lamp
  - Photo-generated holes assist Redox reaction in KOH solution
  - KOH etches the oxidized gallium products
  - HgXe bulb produces a smooth and uniform etch compared with Hg. Etch rate also is different. Rate was Hg) 67 nm/min and HgXe) 150 nm/min.
- **Parameter Space for PEC etching**
  - **Sample Carrier Conc.**
  - **UV light intensity**
  - **Solution type**
  - **Solution conc.**
  - **Temp.**
  - **Agitation**

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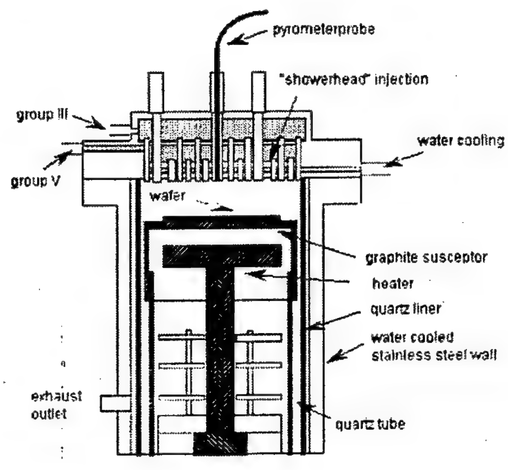
Thomas Swan 3x2" CCS Reactor



- Vertical GaN Reactor
- Water cooled stainless steel outer chamber
- Quartz inner chamber
- Rotating susceptor to improve uniformity
- "Showerhead" injection for efficient gas delivery and mixing
- 3-zone heater for uniform temperature distribution
- Dry Nitrogen purged glovebox enclosure

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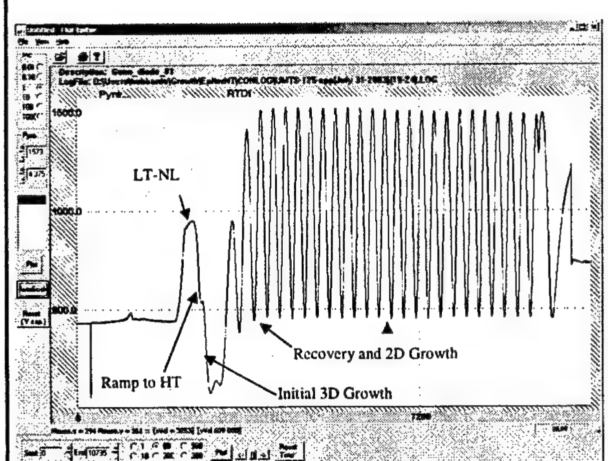
Interferometer Trace



- Interferometer trace shows smooth LT GaN growth then subsequent roughening during the ramp to 1040C.
- After ~1200 sec of 3D growth, HT GaN material is recovered and growing with smooth surface and constant growth rate
- Growth Rate ~ 1.7 μm/hr, consistent with XSEM

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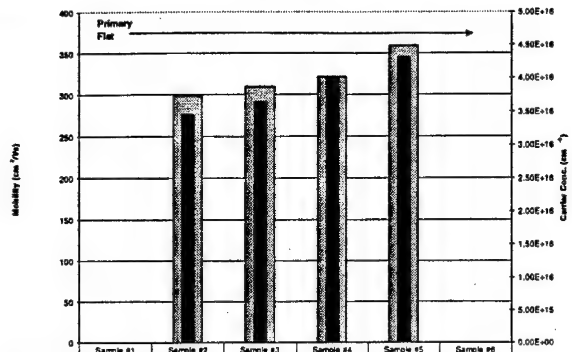
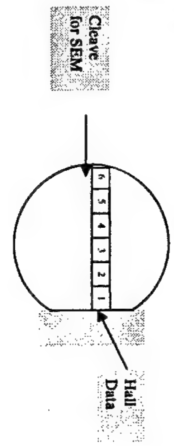
UID Hall Results

UMTS-033 Hall Data



	Sample #1	Sample #2	Sample #3	Sample #4	Sample #5	Sample #6
mobility		298.8471	309.8279	321.6305	359.2551	
carrier conc		3.45E+16	3.85E+16	4.02E+16	4.32E+16	



- Cut 6 300x300 mil (7.5x7.5 mm^2) square for Hall
- Background doping reduced to ~**4x10^{16} cm^{-3}** with corresponding mobility of ~**300** cm^2/Vs.
- Background and mobility appear uniform across the wafer.

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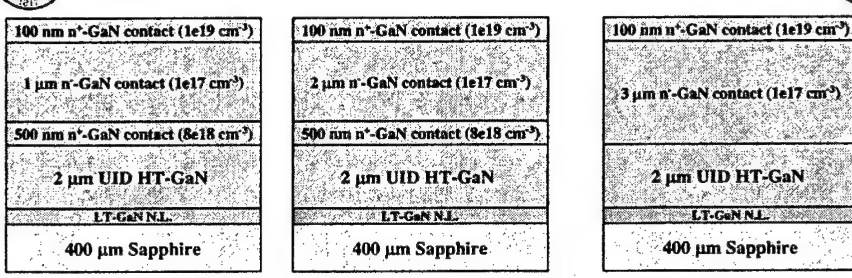
Gunn Diode Structures



1 µm vertical | 2 µm vertical | 3 µm planar

- Calibration of doping for silane flows of 4 sccm=1.0e19 cm^{-3} and 0.05 sccm=1.2e17 cm^{-3}. Curve was generated and silane flow calculated for doping of 1e17, 8e18, and 1e19 cm^{-3}.
- Growth of three Gunn diode structure. Sample 125 is traditional vertical structure with 1 µm active layer. Sample 126 is vertical but with a 2 µm active layer. Sample 128 is a planar Gunn structure with a 3 µm active layer.

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Suppression of Yellow luminescence deep centers of GaN

- **Yellow luminescence center:** a universal feature of GaN located around 2.3 eV.
- **YL source:** electrons from conduction band or a shallow donor to a deep state.
- **Deep state:** Ga vacancy or complex of Ga vacancy with impurity.
- **Effects:** YL centers may influence GaN based device performance
  → high quality GaN layers evidenced by small FWHM/XRC, low noise and large carrier lifetime constants are associated with small YL.
- Use YL to optimize GaN device quality.

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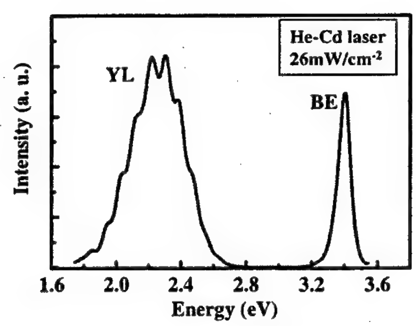
RT Photoluminescence of GaN



Typical PL shows a narrow band edge (BE) peak (~3.4 eV) and broad yellow luminescence (YL) band (~2.3 eV).

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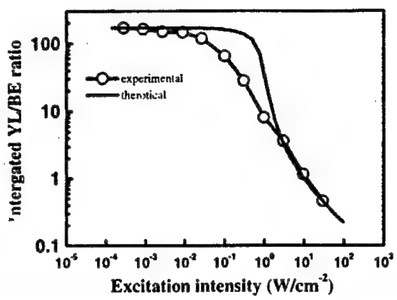
Integrated Yellow to Band edge Luminescence (YL/BE) ratio



- **The experimental data and Shockley-Read –Hall Model calculation agree well at low and high excitation density.**
- **SRH lifetime can be extracted from low excitation region (1.25 ns).**

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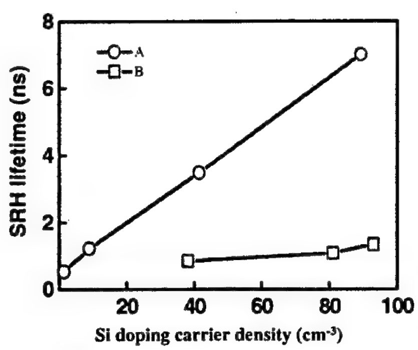
YL of Si doped GaN



Buffer layer growth conditions were changed to study impact on Si-GaN quality

group	Growth time (s)	Ramp time (s)	Re-crystalline time (s)
A	230	300	60
B	200	300	150

(002) FWHM-XRD|$_A$~300",) FWHM-XRD|$_B$~360".

- SRH lifetime of YL centers can be extracted using Hall carrier density N_d and YL to BE ratio.
- The lifetime of YL increases nearly linearly with Si doping density.
- Si substitutes the deep-level Ga vacancy → formation of shallow donor levels decreases YL band (deep level density) → improved material quality ($\tau_{SRH}\uparrow$).
- Si-GaN lifetime increases for high quality buffer layer A.

At low excitation density:

$1/\tau_{SRH} = \sigma_p \upsilon_{th} N_t = (YL/BE) \cdot B \cdot N_d$

B=4.7×10^{-11} cm^3/s (Constant related to band-to-band recombination)

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Growth Pressure and V/III Ratio Effects YL Deep Center

sample	Si doped Carrier density (cm^{-3})	V/III ratio	Pressure (Torr)	SRH lifetime (ns)
A	3.73×10^{18}	**1400**	100	0.34
B	4.33×10^{18}	**800**	100	0.15
C	8.93×10^{18}	1000	**200**	7.0
D	8.43×10^{18}	1000	**100**	0.75

- **High V/III ratio suppresses the Ga vacancy → YL↓ → τ_{SRH}↑**
- **Increase of reactor pressure also reduces V/III ratio → YL↓ → τ_{SRH}↑**
- **SRH lifetime is good indication for growth optimization.**

(high V/III and high pressure needed for improved GaN layer quality)

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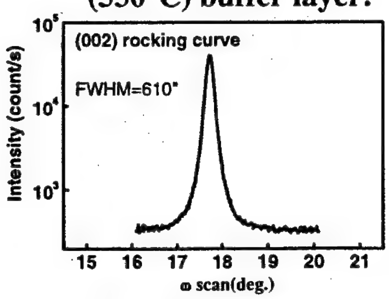
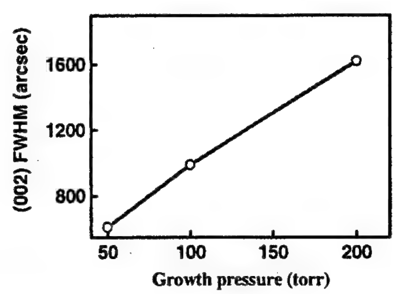
High Quality AlN Growth by MOCVD on Sapphire

1. Growth of AlN (0.4~1 μm) on low temperature (530°C) buffer layer:





- **FWHM-XRD increases with growth pressure.**
- **AlN layer quality is not acceptable (min. FWHM=610") if AlN is grown on sapphire using LT-buffer; Same feature expected using LT-GaN buffer.**

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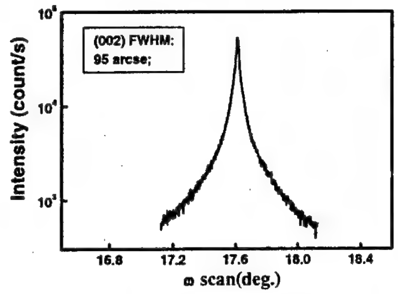
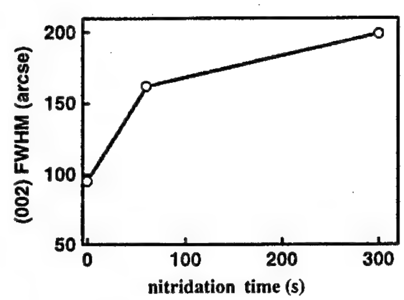
2. Direct growth of AlN on sapphire:





- High quality AlN (0.4 μm) layer was grown on sapphire.
- X-ray rocking curve with excellent FWHM value of 95 arcsec.
- FWHM of x-ray rocking curve is strongly dependent on nitridation time

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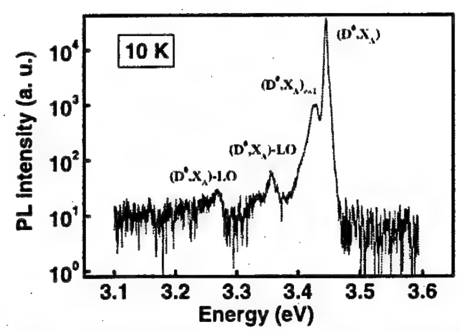
Low Temperature PL of GaN Layers Used in NDR-Diodes



- The main peak is neutral donor bound exciton with FWHM=10 meV.
- Two electron transitions $(D^0, X_A)_{n=2}$; One phonon and two phonon replica were observed.
- The above features indicate high quality samples.

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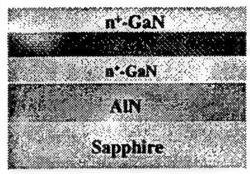
NDR-GaN Diodes Using AlN for Substrateless Design



- The obtained high quality AlN could be used as base for growth of substrateless NDR-GaN Diodes → improved handling of thermal issues.
- Growth of high quality GaN-diode layers on AlN buffer would require following studies for reduced AlN surface roughness.

➢ ALE-like initial AlN growth on sapphire with excess NH_3 flow for reduced layer roughness.

➢ Growth of low XRD FWHM bulk AlN using reduced NH_3 flow.

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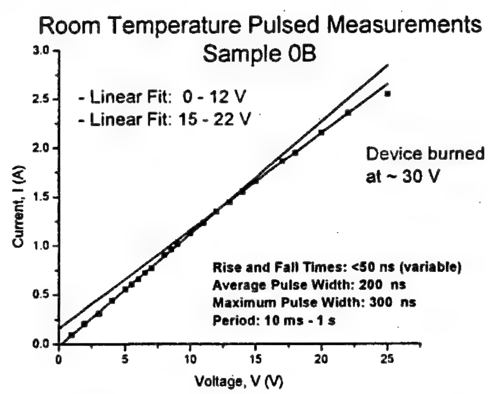
Sample 0B Measurement Results



- RT pulsed IV measurements were performed under following pulse conditions:
  - period: >10 ms; rise/fall time: <50 ns; width: 200 ns; max width: <300 ns
- Slight current saturation begins to onset at > 20 V (100 kV/cm)
- After a sudden spike at ~30 V device is burned and left open.

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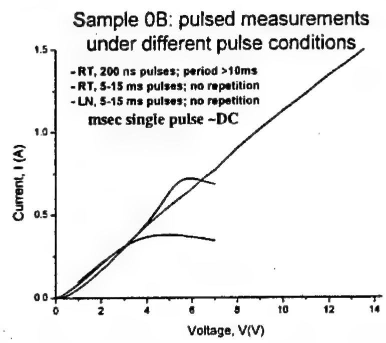
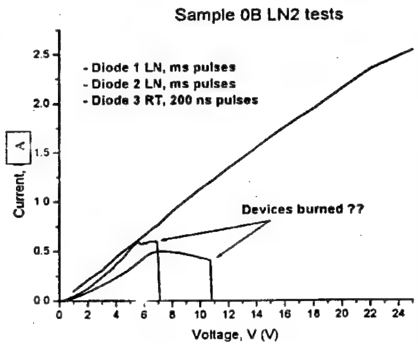
Measurements Under Different Pulse Conditions





- RT measurements under long pulse conditions (~ 300 μs) showed saturation at ~ 300 mA
- Same measurement but at LN2 temperature demonstrated higher peak current at ~ 600 mA and more pronounced NDR
- Under short pulse conditions (pulse width ~ 200 ns) current begins to saturate at ~24 V corresponding to 120 kV/cm even at room temperature

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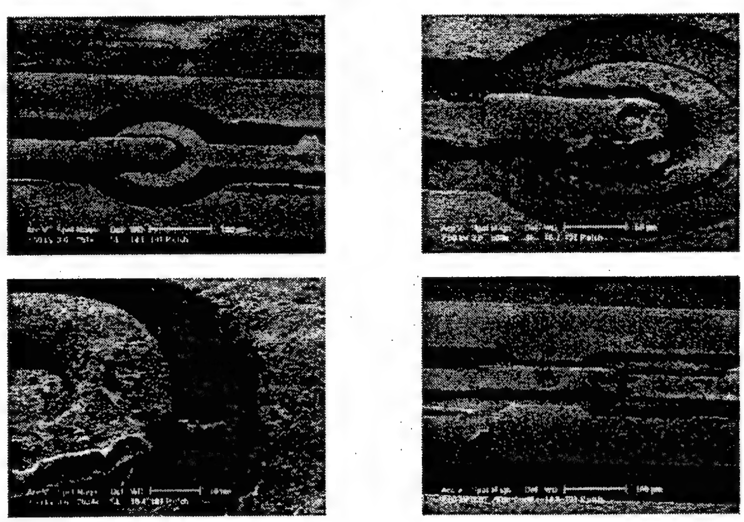
SEM of the Tested Diodes



- Anode contacts burn at high fields

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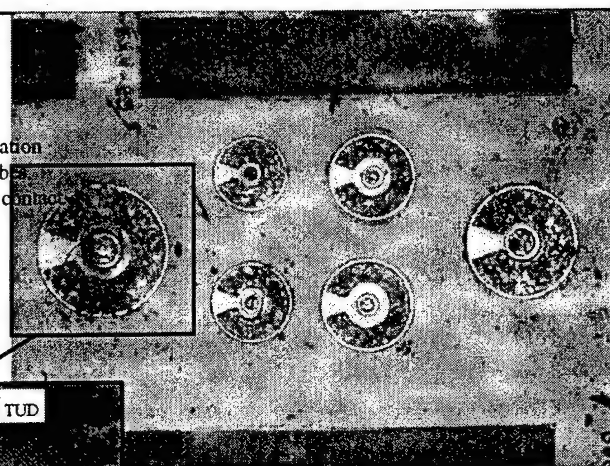
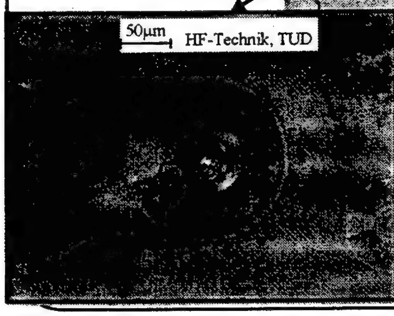
Measured Test Structures
of 00B1. The cathode metallisation
is not wide enough for the probes.
After some measurements the contacts
deteriorate.





Measured Test Structures of 00B1

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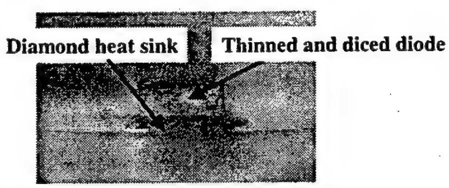
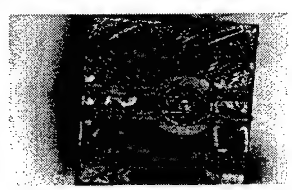
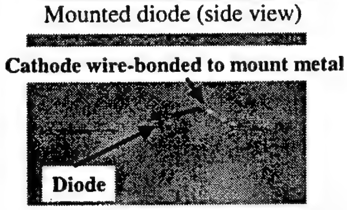
Diodes Mounted on Diamond Heat Sink



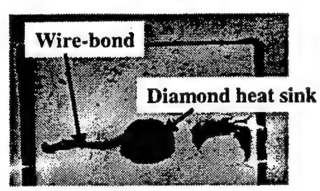
Mounted diode (side view)



Mounted diode (top view)



Mounted diode with wire-bonded cathode
(side view)



Mounted diode with wire-bonded cathode
(top view)

- Collaboration with Quinstar
- Mounting with diamond heat sink improves heat dissipation
  ⇒ reduction of thermal limitation

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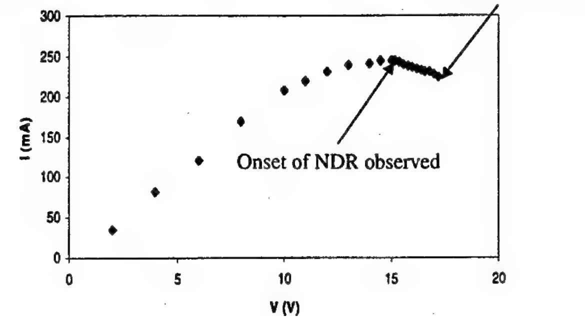
DC Characteristics of Small Gunn Diodes

Sample MICH 01106-1A. Diode diameter: ~15 µm



- Previous measurements of GaN on SiC Gunn diodes with ~ 50-100µm diameter showed onset of NDR at V ~ 12V (Ec ~ 24 kV/cm) with dissipated power ~3-4W
- The critical field for GaN on SiC diodes is well below the predicted values for GaN NDR effect is severely affected by thermal issues.
- Smaller thickness, 0.5µm, diodes on Si have better heat dissipation through the substrate Possibility to observe NDR effects which are less affected by thermal issues.
- Onset of NDR was observed at ~15-16V
- **Corresponding value of the critical field, Ec ~ 300 kV/cm**

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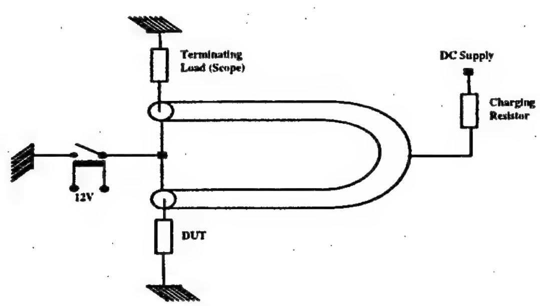
Charged line configuration (Blumlein) for pulse generation



The DC supply Vch is varied between 2 and 500V. The switch is triggered with a period of 100 ms and the trigger pulse of 12V amplitude and 10 ms width (possible to go down to 10 and 2 ms for the period and the width, respectively) is provided by the 8114A pulse generator.
The scope is a 50 Ohm terminating load. With a 50 Ohm DUT the scope waveform is a pulse of negative polarity and Vch/2 amplitude.

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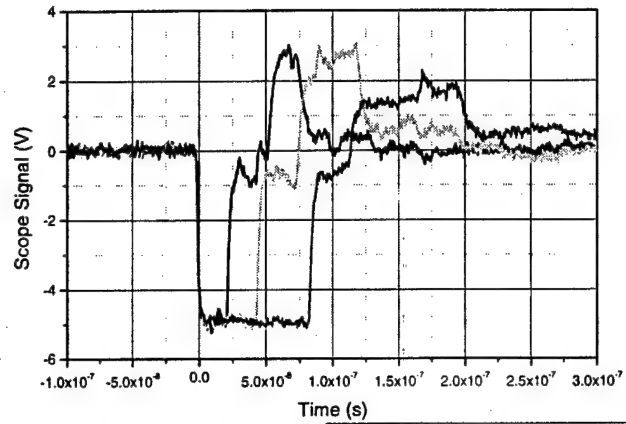
Pulse waveforms with connected diode (00B1) for different pulse widths. The reflected amplitude of the 88 ns pulse is too low, possibly due to poor contacts. There is a 20db atten. Before the scope (max input rms 5V). A factor 10 is to be considered for the voltage scale. The input impedance of the scope is set to 50 Ohm. Pulse waveform @ 100V charge voltage, for 21, 44 and 84 ns pulse width.



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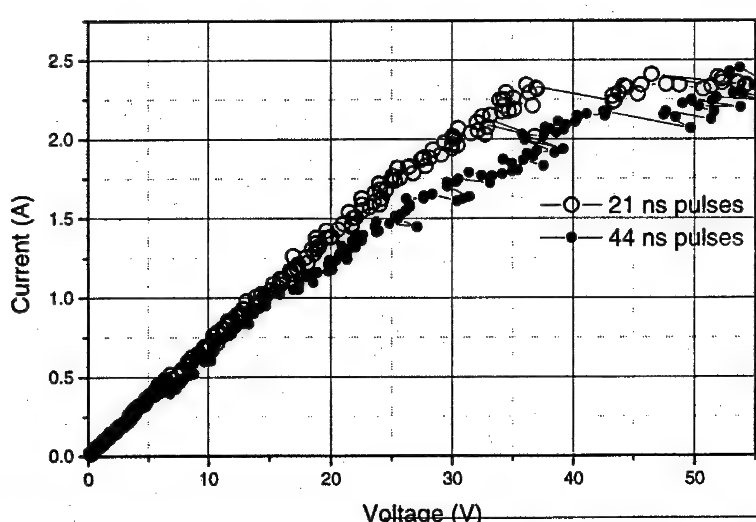
I-V curves of the 00B1 structures (2 micron thick layer) for 2 pulse widths



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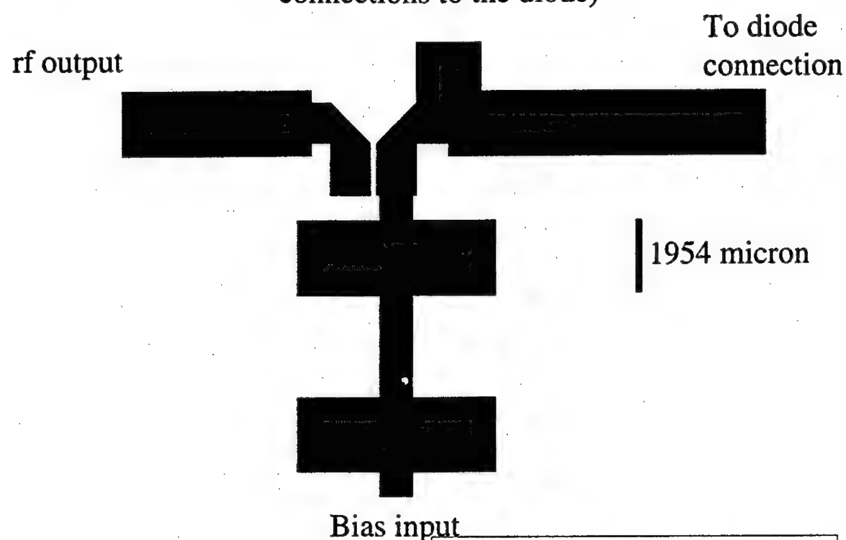
Oscillator layout for 4.6 GHz (Simulation including S-parameters of connections to the diode)



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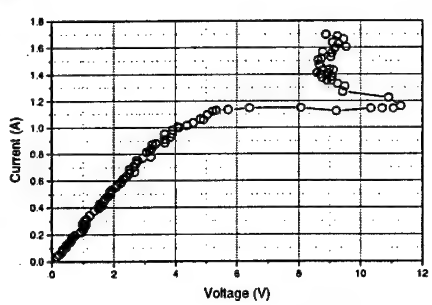
GaAs Gunn Diodes (DC Measurement)



LAYER NR.	MATERIAL	THICKNESS (nm)	DOPING (cm^{-3})	DESCRIPTION
4	InGaAs	50	N (>1 E19)	Cap
3	InGaAs	50	N (5 E18)	In Graded
2	GaAs	10000	N (2 E15)	Gunn layer
1	GaAs Substrate		N (1-3 E18)	

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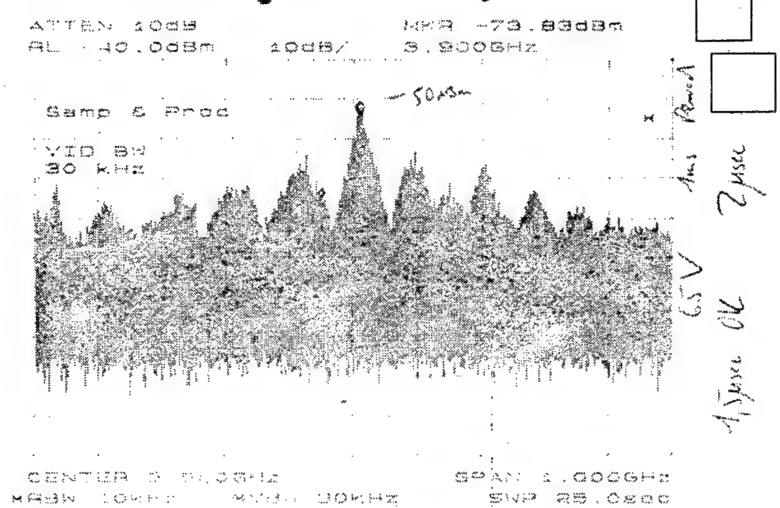
Spectrum analysis of a GaAs Gunn Diode with a resonator



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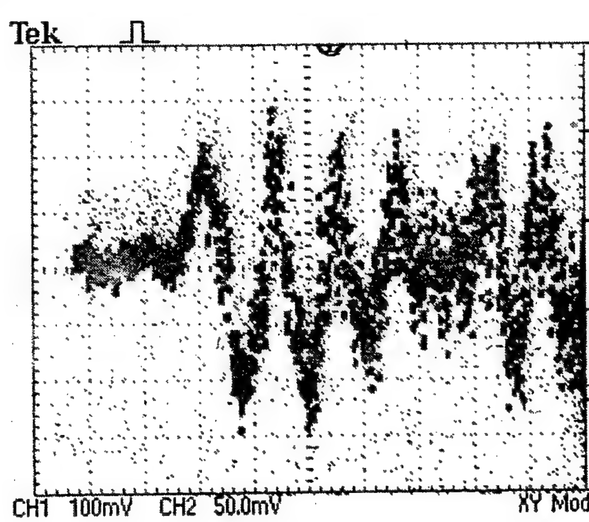
Sampling-Oscilloscope measurement of a GaAs Gunn Diode with a resonator



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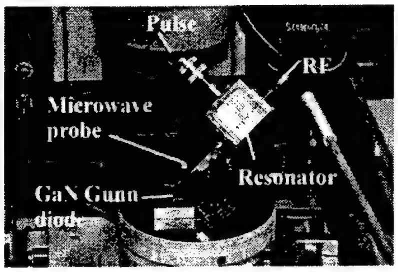
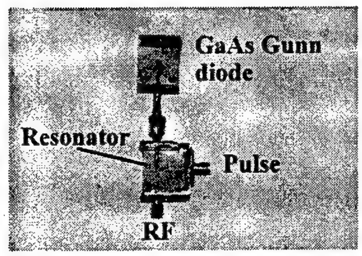


On-wafer measurement setup for Gunn oscillations in GaAs and GaN diodes



Setup for GaAs Gunn-diode testing (10 microns active layer, 150x200 sq. Microns area, Oscillations at 3.9GHz with 200 ns pulses and 100 us repetition rate.

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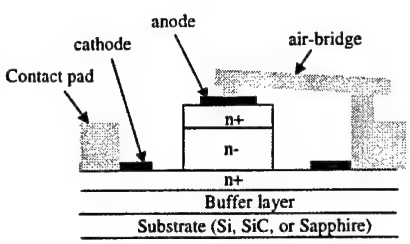
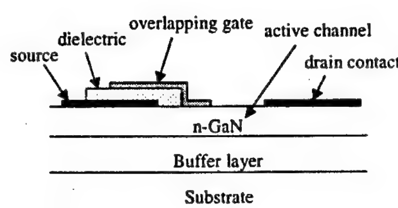
GaN NDR Diode Fabrication

<u>Vertical NDR Structure</u>



- Non-planar approach
- Good thermal dissipation
- Substrate thinning
  ⇨ Integrated heat sink

<u>Horizontal NDR Structure</u>



- Easy integration
- Reduced heat dissipation

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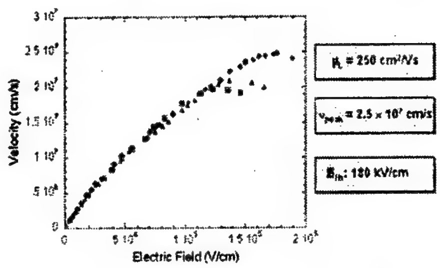
v-F Measurements

Velocity – Field Measurement Results



J. M. Barker, R. Akis, D. K. Ferry, S.M. Goodnick, T. J. Thornton, D. D. Koleske, A.E. Wickenden, and R. L. Henry, *High Field Transport Studies of GaN*, Physica B 314 39-41 (2002)

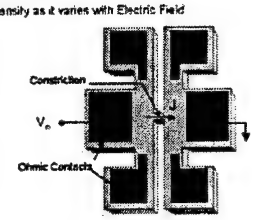
Drift Velocity Measurement

Conductivity Technique (Pulsed IV)

- Measures Current Density as it varies with Electric Field

$$E = \frac{V}{L}$$

$$J(E) = nev_d(E)$$



- Velocity saturation is revealed but no real overshoot prior to breakdown (F_b ~180 kV/cm)
- Test structures burned even under pulsed conditions (t_{pulse} = 200 ns)
- Breakdown is likely due to localized high field in the constriction (< 10 μm)
- Breakdown field is reduced to < 50 kV/cm without passivation
- Transport is along a-axis vs. c-axis in our diode design

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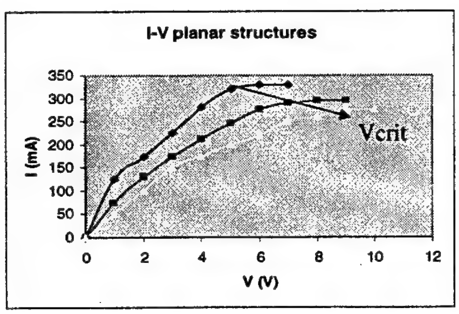
Planar Diode Measurements



- DC measurements of planar TLM-like structures for 3 (black), 6 (purple) , 10 (yellow) μm spacing between pads
- The critical voltage is dependent on the diode length; increases with separation

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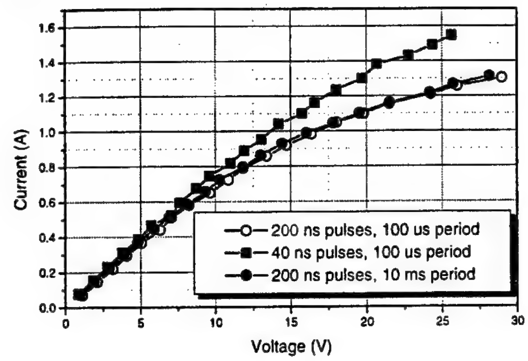

Measurements with planar structures:
3 microns spacing, 40 ns and 200 ns pulses. Saturation tendency, probably due to thermal effects, reached at lower voltage and current for longer pulses independant of the repetion rate. Saturation field about half of corresponding vertical structures (with 2 microns active layer). Beyond 25V important heat development leading to non reproducible results (shift of the saturation current and voltage to lower values), and destruction of the contact metallization.

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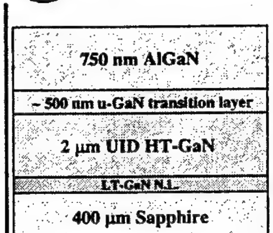
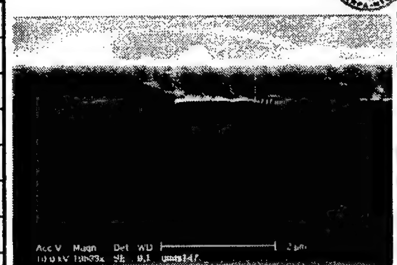
AlGaN Calibration



Temp	1040C
Time	3000 sec
Pressure	100 Torr
Al flow	43 sccm
Ga flow	20 sccm
[Al]/[Al]+[Ga]	25%
NH3 flow	2500 sccm
Growth Rate	0.9 μm/hr



- The TMGa and TMAl flows were selected to give a molar ratio of ~25% Al content. A thick AlGaN layer was grown to facilitate XRD and X-SEM measurements
- Optical micrograph shows AlGaN is cracking due to lattice mismatch induced strain in the thick layer .. This is typical for AlGaN grown direct on GaN.
- X-SEM
  - Cross-Section shows AlGaN/GaN interface very clearly. Growth rate was determined to by ~0.9 μm/hr.

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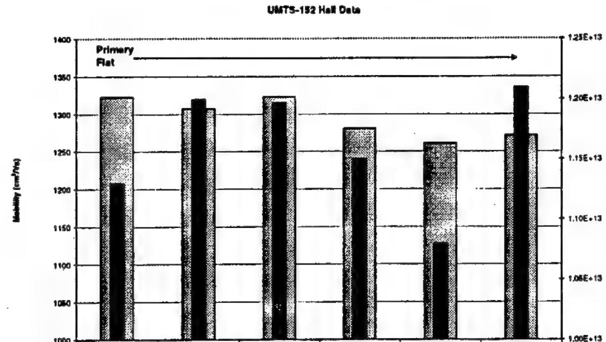
AlGaN/GaN Uniformity



	Sample #1	Sample #2	Sample #3	Sample #4	Sample #5	Sample #6
mobility	1322.898	1307.4248	1323.3981	1281.0808	1261.1444	1271.9645
carrier conc	1.13E+13	1.20E+13	1.20E+13	1.15E+13	1.08E+13	1.21E+13

- Mobility and sheet charge are uniform across the wafer
  - Mobility uniformity less than 5%
  - Charge uniformity less than 10%

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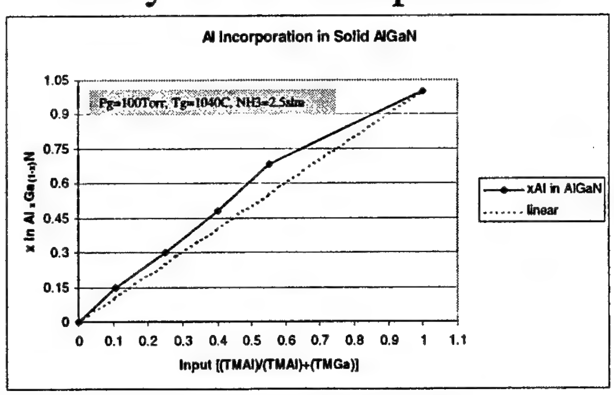
Study of Al Incorporation



- Al incorporation into solid AlGaN shows a super-linear trend
  - We expect reduced Al-NH_3 Pre-reactions due to use of low pressure, low ammonia flow, and close-coupled showerhead reactor design
  - In absence of pre-reaction, quasi-thermodynamic models predict preferential Al incorporation when using high growth temperature and low V/III ratio.
- To verify our data, we are currently studying Al incorporation under various other growth temperature and V/III ratio.

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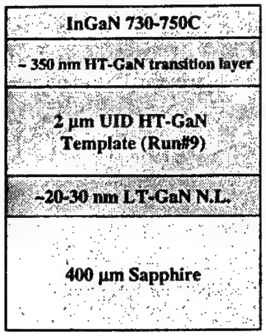
InGaN Calibration



Material	InGaN#1 (#51)	InGaN#2 (#54)	Low Temp. GaN
Growth Temp	730°C	750°C	730-750 °C
Carrier Gas	N_2	N_2	N_2
[TMIn]/([TMIn]+[TMGa])	0.86	0.86	0
Growth Rate	40 nm/hr	80 nm/hr	40-80 hm/hr
XRD-In content	21%	17%	-
NH3	2.5 slm	2.5 slm	2.5 slm
Growth Pressure	200-500 Torr	200-500 Torr	200 Torr

- Thick InGaN was grown directly on GaN to determine growth rate, In content, and layer quality.
  - In content not sensitive to input gas ratio due to In volatility temperature above 500 °C
  - Must change growth temperature or pressure to tune the In content
- LT-GaN also optimized for use in FET to avoid change of growth temperature that could lead to interface degradation

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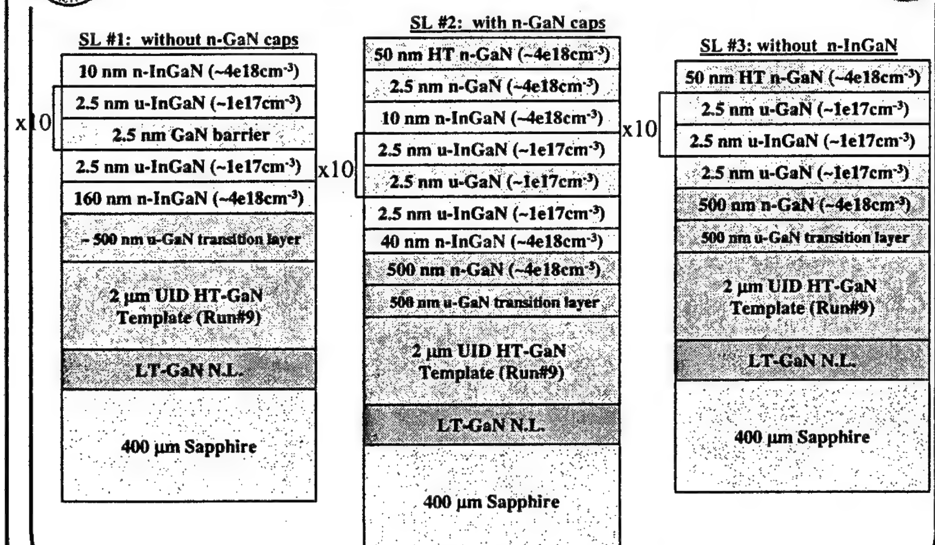
InGaN/GaN SL Growth for Negative Differential Resistance



Nominal In concentration for all InGaN layers ~ 5%

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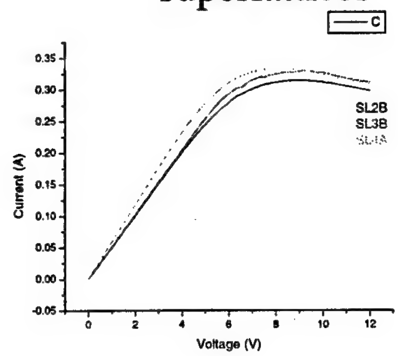
Characterization of InGaN/GaN superlattices



- The I-V characteristic for different structures
- SL2: 10 QWs InGaN/GaN; SL3: 10 QWs GaN/InGaN; SL4: same as SL3 high In%
- All samples processed in parallel and annealed at 750 C

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Breakdown Mechanism

A possible breakdown mechanism between n+ and n- layers is of concern: Apart from a soft recovery, it is necessary that the diode can withstand a high dI/dt, which may result in dynamic avalanche well below the static breakdown voltage. Dynamic avalanche is caused by a current controlled increase of the effective doping level N_{eff} [see Eq. (1)]. J_p is the hole and J_N the electron current density, v_{sat} the carrier saturation velocity, and N_D the n-base doping.

$$N_{eff} = N_D + \frac{J_P - J_N}{q \times v_{sat}}. \qquad (1)$$

Diode destruction by dynamic avalanche during reverse recovery has been reported in Refs. 1–3, but a considerably

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Ohmic Contact Considerations

- At high power the Ti/Al/Au ohmic contacts suffer from severe degradation
- First the contact metal begins to melt around the perimeter of the contacts
- When pushed higher in power the top Au "shoots" across the separation between anode and cathode, eventually violently burning the diode under test
- To remedy this problem a new metallization scheme was used:
    - Ti/Al/Ni/Au contacts were used in recent runs
    - Ni serves as a barrier preventing Au from diffusing into the Ti/Al/GaN contact
    - 10-100 times better quality contacts were achieved (Rsc = 4.4x10-6 Ohm/cm2; previous Rsc = 1.3 x10-4 Ohm/cm2)
- However, at high powers the top Au layer still melts destroying the diode as described above
- Another approach is currently being tested with introduction of refractory metals into the ohmic metallization scheme (Mo, Pt, W, etc.)
- Although refractory metal contacts have usually higher resistance compared with Ti/Al contacts their power handling capability is much higher

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Conclusions I

- High layer quality GaN NDR layers have been grown in house by a newly set up MOCVD facility
- Record quality AlN layers were grown for high thermal conductivity substrateless diodes with improved thermal management.
- GaN Gunn diodes were designed and fabricated on Si substrates with high thermal conductivity. Combined with the use of small size devices they allowed to bias GaN NDR diodes under electric fields suitable for oscillation.
- Liquid Nitrogen Characterization of GaN NDR diodes manifested clear increase of current handling as necessary for establishment of NDR conditions.
- Planar GaN NDR diodes have been investigated as an alternative to vertical designs.

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Conclusions II

- InGaN/GaN superlattice designs have been theoretically and experimentally investigated for THz signal generation.
- Pulse generation setups have been developed to respond to high power, nsec time needs of GaN NDR diodes. On wafer probe techniques with built-in resonators have been investigated for high frequency testing of NDR diodes.

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THz Micromachined Structures

Yongshik Lee, Jack East and Linda Katehi
The University of Michigan

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Outline

- **Overview & Background**
- **Thz micromachined structures**
- **Summary**

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THz Micromachined Structures

- Goal is to develop silicon and GaAs micromaching technology
- The resulting processes can be used to realize low cost batch fabricated structures from 100 GHz to several THz
- Probes, waveguides, transitions and flanges have been developed and tested
- Continuing efforts will focus on WR10, Wr5 and WR3 circuits and systems

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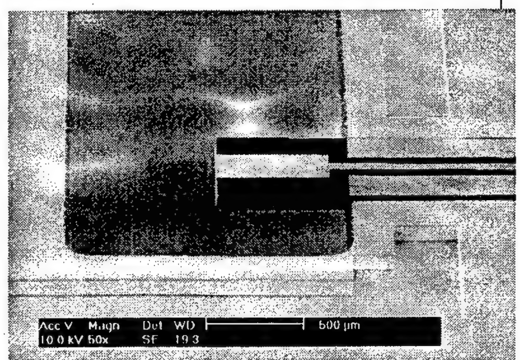
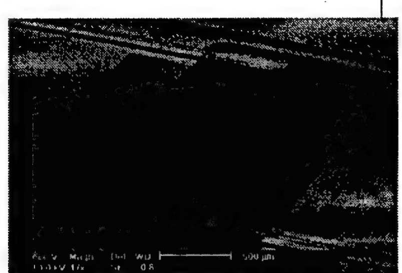
Deep RIE (DRIE) Technology

- Goal is to realize micromachined elements that can be scaled to THz frequencies
- Design based on HFSS
- Technology based on conventional lithography and a STS deep etch tool
- Example WR 10 waveguide and transition



DRIE (continued)

- Complex structures such as coupling probes positioned with integral backshorts can be fabricated
- Excellent control of dimensions possible
- Assembly and alignment will be critical at higher frequencies
- Batch techniques will be needed to reduce cost



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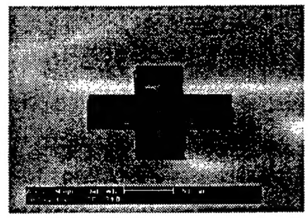
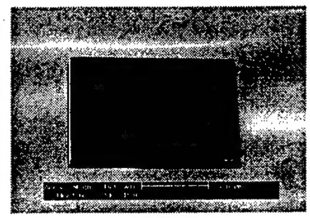
DRIE (continued)

- Assembly and alignment will be critical at higher frequencies
- Batch techniques will be needed to reduce cost
- Alignment "pins" and "holes" can be easily included as part of the design





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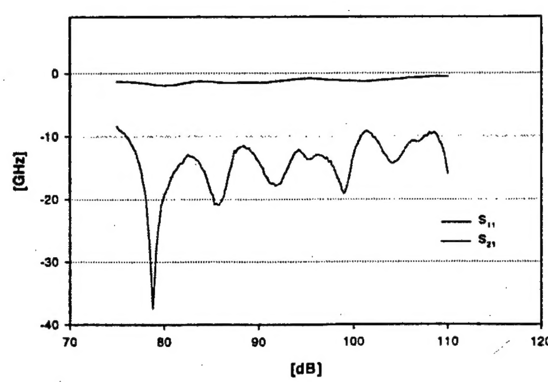
Transition Results

FGC-to-DRIE Waveguide Transition



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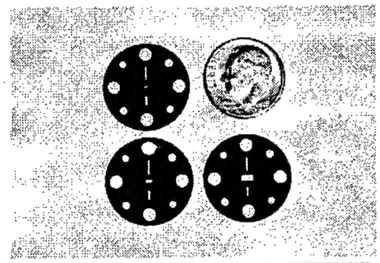
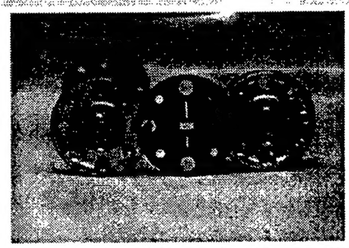
Waveguide Transitions

- We also need transitions to external waveguide assemblies
- Batch fabrication and accurate low cost alignment and assembly will be critical





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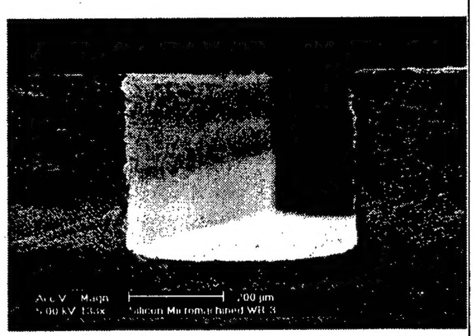
WR3 DRIE Waveguides

- Nearly vertical walls with slightly curved bottom
- Excellent cross section dimensional control
- Initial surface roughness reasonable, can be improved with slower etching and oxidation smoothing
- CST analysis shows excellent return loss with expected misalignment



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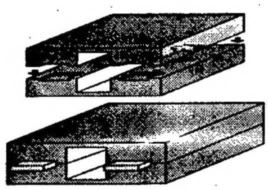
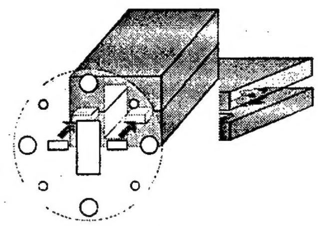
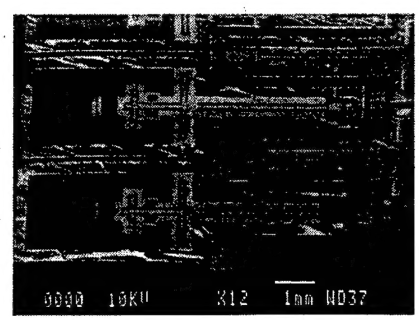
Flange Alignment & Assembly





GaAs Etched Chemistry Development

- New effort this year to micromaching GaAs structures
- Etching chemisty and masking requirements from silicon
- Initial results good for W band multiplier chips
- Additional optimization needed for thinned chips and substrateless waveguide transitions



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Project Summary

- Experimental micromachining technology developed for silicon
- Waveguide, probes, transitions and flanges developed and tested in W band
- Excellent experimental results in W band
- Nearly finished with corresponding GaAs process technology
- Technology demo with complete W band multiplier
- Ongoing efforts to use technology up to 325 GHz

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